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VEHICLE ACCELERATION AND FUEL CONSUMPTION WHEN OPERATED ON JP-8 FUEL

INTERIM REPORT
BFLRF No. 257

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A limited test program (eight combat and tactical vehicles) was conducted to obtain a quantitative estimate of the change in combat and tactical vehicle performance and fuel consumption that would occur when converting the military fleet to MIL-T-83133 JP-8 (F-34) fuel. Data specifically desired included startability and idle quality, acceleration rates, and fuel consumption. Also, a comparative assessment of the on-vehicle smoke production capabilities of combat vehicles with the two fuels was desired. As a result of these tests, it was determined that substitution of JP-8 for DF-2 reduced the acceleration rates, and thus power, of all vehicles tested except for the M928 and M1009 vehicles, which improved or remained the same. Also, all vehicles tested, except for the M88A1 light recovery vehicles, had fuel consumption increases with JP-8 that were at or below that predicted by the heating value difference between the two fuels. No drivability or idle problems occurred with any of the test vehicles.

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EXECUTIVE SUMMARY

Problems and Objectives: In the March 1988 U.S. Department of Defense Directive No. 4140.43, Fuel Standardization, the Department of Defense adopted the single fuel for the battlefield concept. JP-8 (NATO Code F-34) has been chosen to replace VV-F-800 DF-2 (NATO Code F-54) in all combat and tactical vehicles throughout NATO. Since JP-8 has a lower energy content per gallon than DF-2, reduced engine power and increased fuel consumption were expected. However, the actual effects of the JP-8 fuel on vehicle fuel consumption and acceleration were not known. This program was conducted to provide initial data in quantifying those effects.

Importance of Project: To determine the logistical effect of using JP-8 as the only fuel for combat and tactical vehicles, tests must be performed using military vehicles operating in typical field environments. The results of these tests can then be used in conjunction with other more comprehensive data to determine the amount of JP-8 fuel that must be supplied to military combat vehicles.

Technical Approach: The vehicles for this limited testing program were based on equipment density, engine type, and mission profile. Tests were performed with these eight vehicles to determine fuel consumption, acceleration capabilities, as well as operation of the vehicle engine exhaust smoke system, using first diesel fuel and then JP-8 fuel. The actual difference in these parameters would be noted.

Accomplishments: Under the conditions of this limited testing of eight vehicles, it was determined that the use of JP-8 reduced the acceleration rates, and thus power, of all tested vehicles except the M928 and M1009 vehicles. The acceleration rates in the M1009 remained unchanged while the rate was actually increased in the M928. Also actual fuel consumption was determined in the vehicles. For example, fuel consumption in the M928 vehicle increased by only 4 percent when using JP-8 fuel as opposed to DF-2; the M1009 fuel consumption increased by 5.2 percent. Other vehicles had increases in fuel consumption that were equal or lower than the 6.65 percent predicted from the heating value difference between the test fuels. The only exception was the M88A1 light recovery vehicle, which had higher than predicted fuel consumption.

Military Impact: The estimate of the amount of JP-8 fuel required to maintain mobility for the military vehicles has been improved, and vehicle performance changes have been quantified. These data can be used with other more extensive data concurrently being generated to determine if any vehicle modification or logistics changes may be required.

FOREWORD/ACKNOWLEDGMENTS

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The author would like to specifically acknowledge Mr. Alan Montemayor, who developed and supported the on-vehicle equipment and instrumentation; Messrs. Greg Phillips, Ruben Alvarez and Jim Barbee, who conducted the field testing; and Ms. Janet P. Buckingham, who provided guidance and support in the statistical analysis of the resulting data. Special thanks also go the BFLRF reports processing staff for its typing and editorial assistance.

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I. INTRODUCTION

A limited series of vehicle tests were conducted to quantify the fuel consumption and acceleration time differences resulting from changing from DF-2 to JP-8 fuels and to evaluate the vehicle engine exhaust smoke system (VEESS). Testing was conducted at Fort Bliss, TX; Fort Hood, TX; and Fort Benning, GA. Selection of the vehicles for testing was based on equipment density, engine type, and mission profile. The 11th Air Defense Artillery Brigade at Fort Bliss provided vehicles and crews for the M1009 CUCV, M928 5-ton truck, and the M113A2 personnel carrier. The 3rd Armored Cavalry Regiment at Fort Bliss provided an M88A1 recovery vehicle and a M1A1 main battle tank. A retest of the M88A1 was conducted at Fort Hood with the support of the 49th Armored Division National Guard. At Fort Benning, an M60A3 tank and crew were provided by the 69th Armored Battalion and an M3 Infantry Fighting vehicle and crew from the 29th Infantry Regiment.

II. BACKGROUND

A proposed conversion from JP-4 to JP-8 for aircraft within NATO to increase safety, reduce vulnerability, extend operating range, and enhance commercial availability was introduced in 1976. However, because of questions on cold startability of helicopters, increased fuel price differential, and concerns about fuel availability during wartime operations, the conversion process was delayed during the late 1970s as nations were reluctant to ratify this conversion until all issues had been resolved.

With the introduction of the M1 tank and other gas turbine equipment into Germany in late 1981, JP-5 and JP-8 were blended with NATO standard diesel, F-54, to solve a severe low-temperature fuel-waxing problem. The procedure was successful, and it became policy that all fuel during the winter would be blended prior to exiting the Class III supply points. NATO countries, recognizing pending conversion, began to explore the potential of using other commercially available fuels to reduce low-temperature operability problems.

A United States-published report entitled "JP-8 and JP-5 as a Compression-Ignition Engine Fuel," (1)* in 1985 confirmed the feasibility of using JP-8 in lieu of F-54 diesel fuel; in early

* Underscored numbers in parentheses refer to the list of references at the end of this report.

1986, HQ AMC acknowledged acceptability in using JP-8 as an alternate to diesel fuel. NATO countries agreed to convert from NATO Code No. F-40 (JP-4) to F-34 (JP-8) effective 1 January 1987.

With this planned conversion, the concept of a single fuel for the battlefield became a reality with significant logistical and operational advantages. Use of NATO Code No. F-34 (JP-8) in diesel-fueled vehicles and equipment will resolve many fuel-related low-temperature operability problems that are being experienced. Further, it may reduce a wide variety of fuel-related maintenance problems that have been occurring with diesel fuel usage and increase the life of the engine lubricant. All nations in NATO are working toward this common goal. The only major problem encountered thus far within the United States is the question of JP-8 smoking characteristics in combat vehicles' vehicle engine exhaust smoke systems (VEESS). Tests are underway to determine the feasibility of a simple mechanical fix or fuel fix.

III. OBJECTIVE

The objective of this effort was to obtain a quantitative estimate of the change in combat and tactical vehicle performance and fuel consumption that would occur when converting from VV-F-800D DF-2 to MIL-T-83133 JP-8 fuel. Data were specifically desired on vehicle startability and idle quality, acceleration rates, and fuel consumption. A comparative assessment of the on-vehicle smoke production capabilities of combat vehicles with the two fuels was also desired.

IV. APPROACH

Critical or widely used combat and tactical vehicles were selected as desirable candidates for testing. Testing sites, preferably in warm climates, where the desired vehicles would be available were contacted, and the necessary access and vehicle use arrangements were made. Each of the test vehicles was drawn from current Army inventories and, except for the M88A1 medium recovery vehicles, were selected and assumed to be "average" fielded vehicles.

To facilitate testing and control, a separate fuel supply system was fitted to the vehicles to enable back-to-back testing of the two fuels on each vehicle. Two well-characterized test

fuels were used for all testing. Adequate instrumentation was installed to monitor various vehicle operating temperatures and to accurately measure the small amounts of fuel consumed during these brief tests.

V. TEST DETAIL

A. Equipment

The following equipment was used in this program:

- Fluidyne fuel flow transducer with digital timer/totalizer/indicator
- Day tank
- Fuel-to-air heat exchanger
- 8-channel data logger
- Video camera
- Calibrated stop watches
- Fuel transfer pump
- Bosch smoke meter with tail pipe probe
- Calibrated portable tachometer with adapter for CUCV
- External fuel tanks
- Metal stakes for markers

B. Test Vehicles

The vehicles to be tested were chosen to represent a cross-section of engine types. The actual vehicles supplied at each test site were selected by the local organizations based on availability of vehicles and crews. Because of questions with the results generated from the M88A1 test at Fort Bliss, TX, the M88A1 used at Fort Hood was specifically requested to be the lowest mileage, newest vehicle available. The vehicle descriptions and estimated test weights are given in TABLE 1.

TABLE 1. Test Vehicle Description

Vehicle	M Series	Test Site	Serial Number	Engine	Odometer	Hour Meter	Estimated Test Weight, lb
Commercial Utility Cargo Vehicle	M1009	Ft. Bliss	NFOJUX	GeneralMotors 6.2L	6465	N/A*	5,900
5-Ton Cargo Truck LWB	M928	Ft. Bliss	NLONKD	Cummins NHC-250	2406	84	26,250
Armored Personnel Carrier	M113A2	Ft. Bliss	MSJ19146MAA	Detroit Diesel 6V-53N	1442	171	23,159
Medium Recovery Vehicle	M88A1	Ft. Bliss	JTOORC	Teledyne Continental AVDS-1790-2DR	4181	385	105,990
Main Battle Tank	M1A1	Ft. Bliss	07085J203Q1	Avco-Lycoming AGT-1500	3798	596	126,990
Medium Recovery Vehicle	M88A1	N. Ft. Hood	BMY2593	AVDS-1790-2DR	402	44	105,900
Cavalry Fighting Vehicle	M3	Ft. Benning	3AA00737	Cummins VTA-903T	4764	N/A	41,759
Main Battle Tank	M60A3	Ft. Benning	2592A	AVDS-1790-2C	2861	166	105,160

* N/A = Not Applicable.

On tracked vehicles, track tension was adjusted prior to testing and checked after testing. As a check for transmission torque converter integrity, the torque converter stall speeds of the M1009 and M928 were measured prior to testing. Both vehicles were within specification. During this procedure, Bosch smoke measurements were made with both fuels. Each measurement was conducted five times.

C. Test Fuels

The JP-8 fuel was blended so that the fuel viscosity was close to the average viscosity of JP-8 being procured by the U.S. Military.(2) The fuel met all the requirements of MIL-T-83133B, Grade JP-8. The DF-2 fuel was blended for the Caterpillar 1G/1H test procedure and met the requirements of Federal Specification VV-F-800D. The inspection properties of the two test fuels (AL-17629-F and AL-17696-F) are given in TABLE 2. Thus, both fuels were "specification quality fuels."

Both viscosity and heating value of the fuel are important in comparisons of acceleration and fuel consumption. Fuel viscosity affects the full rack (full power) fuel delivery rate to the engine, affecting acceleration times. Changes in the fuel's net heat of combustion, i.e., energy content per gallon, change fuel consumption irrespective of any other engine response to the fuel substitution. Fig. 1 illustrates the range of kinematic viscosities for JP-8 reported in Ref. 2, and indicates where the test fuel used in this program falls. TABLE 3 estimates heating values for fuels of military interest and compares these fuels to the test fuels.

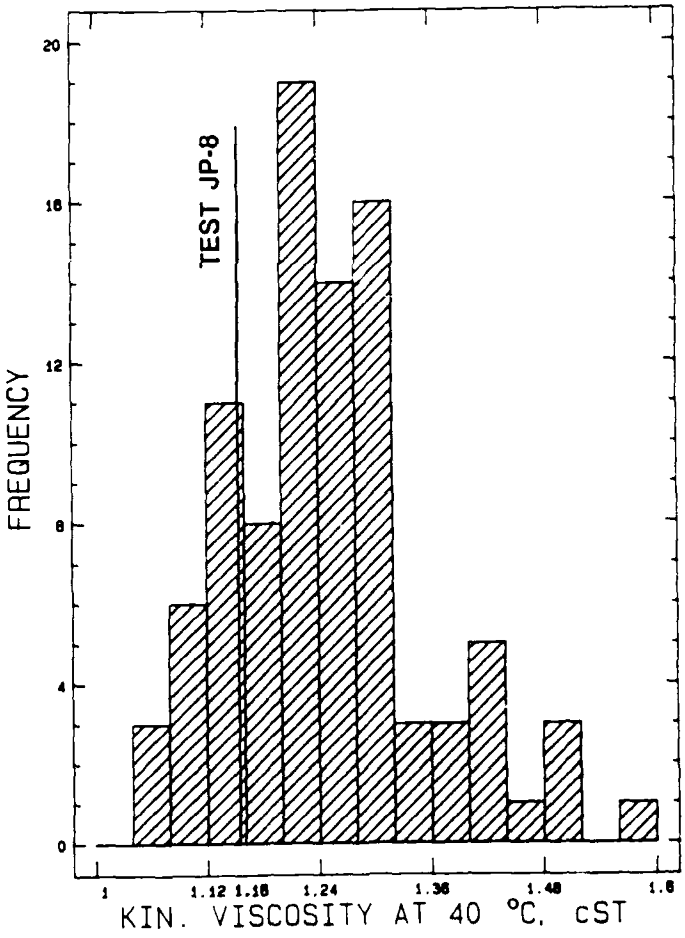


Figure 1. Frequency histogram, JP-8, kinematic viscosity at 40°C (Ref 2)

TABLE 2. Properties of JP-8 and Reference No. 2 Diesel Fuel (Cat 1H)

Property	Method	JP-8 MIL-T-83133C Requirements	JP-8 AL-17629-F	DF-2 VV-F-800D Requirements	DF-2 AL-17696-F
Visual Appearance	D 4176	Clean/Bright	ND (1)	Clean/Bright	ND
Saybolt Color	D 156	Report	>+30	NR (2)	ND
Total Acid No., mg KOH/g	D 3242	0.015, max	0.004	NR	ND
Neutralization No., mgKOH/g	D 974	NR	ND	0.10, max	0.16
Aromatics, vol%	D 1319	25.0, max	9.3	NR	ND
Olefins, vol%	D 1319	5.0, max	1.5	NR	ND
Sulfur, Total, mass%	D 2622	0.3, max	0.03	0.30, max	ND
Sulfur, Total, mass%	D 4294	0.3, max	ND	0.30, max	0.41
Mercaptan Sulfur, mass%	D 3227	0.002, max	<0.0001	NR	ND
Distillation, °C	D 86				
Initial Boiling Point		Report	168	NR	210
10% Recovered		205, max	178	NR	237
20% Recovered		Report	181	NR	245
50% Recovered		Report	188	Report	268
90% Recovered		Report	204	357, max	317
End Point		300, max	216	370, max	353
Residue, vol%		1.5, max	0.5	3, max	0.5
Loss, vol%		1.5, max	0	NR	0
Flash Point, °C	D 56	NR	ND	52, min	84
Flash Point, °C	D 93	38, min	47	NR	ND
Gravity, °API	D 1298	37-51	49.4	NR	34.3
Density, 15°C, kg/L	D 1298	0.755-0.840	0.7819	0.815-0.860	0.8530
Freeze Point, °C	D 2386	-47, max	-47	NR	ND
Cloud Point, °C	D 2500	NR	ND	Local	-5
Pour Point, °C	D 97	NR	ND	Report	-7
Kinematic Viscosity, cSt, at	D 445				
-20°C		8.0, max	3.68	NR	ND
40°C		NR	1.16	1.9-4.1	2.92
70°C		NR	0.82	NR	1.75
Net Heat of Combustion,	D 240				
Btu/lb		18,400, min	18,600	NR	18,260
MJ/kg		42.8, min	43.264	NR	42.474
Btu/gal.		NR	121,123	NR	129,755
Hydrogen, mass%	D 3178	13.4, min	14.4	NR	13.04
Smoke Point, mm	D 1322	25.0, max	29.5	NR	ND
Copper Corrosion	D 130				
2 hours at 100°C		1B, max	1A	NR	ND
3 hours at 50°C		NR	ND	1, max	1A
Thermal Stability (JFTOT),	D 3241				
Visual Code		<3, max	1	NR	ND
Change in Pressure Drop, mmHg		25, max	0	NR	ND
Existent Gum, mg/100 mL	D 381	7.0, max	0.2	NR	ND
Particulate Matter, mg/L	D 2276	1.0, max	0.5	10, max	1.0
Accelerated Stability, mg/100 mL	D 2274	NR	ND	1.5, max	1.0
Water and Sediment, vol%	D 1796	NR	ND	NR	0.05
Water Reaction, Interface Rating	D 1094	1B, max	1	NR	ND
Water Separation Index, Microsep	D 3948	70, min	60	NR	ND
Fuel System Icing Inhibitor	FED-STD-791, Method 5340	0.10-0.15	0.11	NR	ND
Corrosion Inhibitor, mg/L	HPLC	NR	9	NR	ND
Fuel Electrical Conduct., pS/m	D 2624	150-600	130	NR	ND
Cetane Number	D 613	NR	49	45, min	50
Cetane Index	D 976-80	NR	48	43, min	46
Aniline Point, °C	D 411	NR	66.8	NR	ND

(1) Not Determined.
(2) No Requirement.

TABLE 3. Calculated Net Heat of Combustion for Selected Fuels

Property	Test DF-2 (AL-17696-F)	DF-2	F-54	F-64	JP-8 (F-34)	Test JP-8 (AL-17629-F)
Density at 15°C	0.8530	0.8524	0.8330	0.8162	0.7995	0.7819
Gravity, °API	34.3	34.5	38.3	41.9	45.4	49.4
Net Heat of Combustion	129,755	130,319	127.776	125,457	123,138	121,123
% Less Btu/gal than DF-2	0	0	-2.0	-3.7	-5.5	-6.7*

*Based on DF-2 test fuel.

The JP-8 selected for this test was specifically blended to be of lower viscosity and lower energy content than the average JP-8. This blend was prepared so that the data generated would represent a "worst case" for both acceleration and fuel consumption changes. From a European NATO perspective, however, the acceleration and fuel consumption changes indicated here may be much greater than what will actually be experienced. As indicated in TABLE 3, the European F-54 fuel currently being delivered within NATO is already lower in energy content than the reference fuel used in this work. Thus, the energy content change upon conversion may be as little as 4 percent rather than the almost 7 percent difference between these two test fuels. This difference would naturally affect both the acceleration and fuel consumption changes experienced upon conversion.

D. Equipment Installation

Measurements were taken of each vehicle configuration to determine the best method to install instrumentation and fuel lines. The different lengths of fuel lines were fabricated from 0.5-inch (12.7 mm) steel-braided, high-pressure hose. A 0.5-inch male pipe fitting at each end of the hoses permitted attachment to the quick disconnects and fittings of the different engines.

The fuel flow transducer, day tank, digital totalizer, fuel filter, and data logger were mounted in a specially fabricated box with quick disconnects at the fuel inlet and outlet for easy installation on the test vehicle.

Fig. 2 illustrates the fuel supply system for the test vehicles. The fuels were supplied from separate external 30-gallon tanks securely strapped to the outside of the vehicles. A 101-gph, 14-psi 12 VDC fuel pump mounted at the fuel tank outlet supplied fuel to the systems. The fuel flow, therefore, was from the externally mounted tank, through the fuel pump, to the filtering system, through the transducer to the day tank and finally to the engine. The return fuel flowed through the heat exchanger back to the day tank.

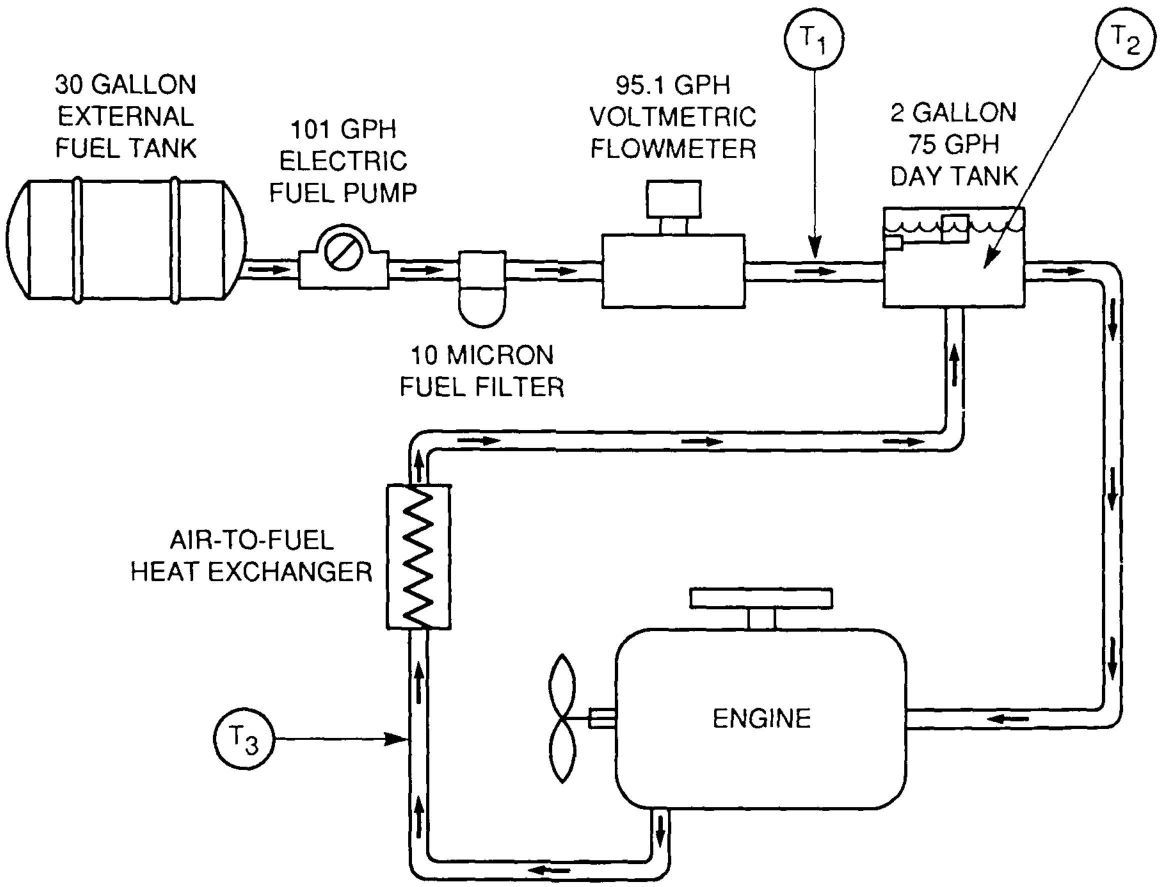


Figure 2. __Illustration of fuel supply system for test vehicles__

Deviation from the above fuel routing was necessary on the M88A1 recovery vehicle, the M60 tank, and the M1A1 main battle tank. An additional fuel pump was installed at the day tank outlet to supply enough fuel to the M88A1 and M60. Since the M1A1 does not have a fuel return, the day tank was bypassed, and the fuel flowed directly from the external fuel tank and pump, through the transducer, and then to the engine.

Thermocouples were attached to data-logging equipment, and measurements were taken during each test procedure. Thermocouples were installed in the following locations:

- Fuel into the flow meter and day tank
- Fuel from day tank to engine
- Fuel return from engine (except M1A1) prior to the heat exchanger
- Engine oil sump
- M88A1 only:

    Exhaust temperature at turbine scroll (1 only)

    Inside exhaust pipe at exit (1 per side)
- M60 only:

    Inside exhaust pipe at exit (1 per side)
- M1A1 only:

    Inside exhaust outlet 9 inches from exit.

E. Test Sites

1. Fort Bliss, TX

The test locations were selected by on-site personnel based on guidance provided by BFLRF staff. The Fort Bliss test track selected for the M1009, M928, and M113 was a smooth hard-packed, gravel road running east-to-west. The road curved moderately to the northeast approximately 1.6 miles from the west starting point. However, the curve was negotiable at test speeds and did not impair the test requirements. Also, approximately 0.8 mile from the west starting point, there was a paved section of roadway, which was used to conduct the acceleration runs.

Due to the weight classification of the M88A1 and the M1A1 vehicles, it was necessary to select a different site to test these vehicles. The test track selected for the M88A1 and M1A1 vehicles was a smooth, straight, soft sand road running south-to-north. The roadway had a slight south-to-north gradient. Ambient temperature, relative humidity, wind speed, and direction were measured at the beginning of each portion of testing (TABLE 4).

TABLE 4. Climatic Conditions at Test Site

Type Vehicle	Type Test	Ambient Temp °C (°F)	Relative Humidity, %	Wind Velocity, mph/ Direction	Type Fuel	Test Speed	Number Replicates
Ft. Bliss, TX (3956 ft. above sea level)							
M1009	ACC*	31 (87)	19	6.3 NW	DF-2	20-30-40	6
M1009	ACC	31 (87)	19	6.3 NW	JP-8	20-30-40	6
M1009	FC	35 (95)	20	6.3 NW	DF-2	30-50	4
M1009	FC	36 (96)	22	6.3 NW	JP-8	30-50	4
M928	ACC	34 (94)	21	0.5 NW	DF-2	20-30-40	6
M928	ACC	34 (94)	21	0.5 NW	JP-8	20-30-40	6
M928	FC	29 (84)	41	0.5 NW	DF-2	30-40	4
M928	FC	29 (84)	41	0.5 NW	JP-8	30-40	4
M113A2	ACC	34 (93)	29	12.0 SE	DF-2	10-20-30	6
M113A2	ACC	34 (93)	29	12.0 SE	JP-8	10-20-30	6
M113A2	FC	31 (97)	39	12.0 SE	DF-2	20-30	4
M113A2	FC	33 (92)	34	12.0 SE	JP-8	20-30	4
M88A1	ACC	34 (93)	31	6.0 E	DF-2	10-20-25	6
M88A1	ACC	34 (93)	31	6.0 E	JP-8	10-20-25	6
M88A1	FC	29 (85)	39	0	DF-2	15-25	4
M88A1	FC	31 (87)	43	6.0 E	JP-8	15	4
M88A1	FC	37 (98)	27	4.0 E	JP-8	25	4
M1A1	ACC	35 (95)	26	5.0 NE	DF-2	10-20-25	6
M1A1	ACC	35 (95)	26	5.0 NE	JP-8	10-20-25	6
M1A1	FC	35 (95)	26	5.0 NE	DF-2	20-30	2
M1A1	FC	35 (95)	26	5.0 NE	JP-8	20-30	2
North Ft. Hood, TX (905 ft. above sea level)							
M88A1	ACC	34 (94)	64	6.5-9 SE	DF-2	10-20-25	6
M88A1	ACC	28 (83)	78	3 NW	JP-8	10-20-25	6
M88A1	FC	34 (94)	64	3NW	DF-2	15-20	4
M88A1	FC	28 (83)	78	3NW	JP-8	15	4
M88A1	FC	34 (93)	64	3NW	JP -8	20	4
Ft. Benning, GA (397 ft. above sea level)							
M3	ACC	27 (80)	70	0	DF-2	10-20-30	6
M3	ACC	27 (80)	70	0	JP-8	10-20-30	6
M3	FC	22 (72)	71	0	DF-2	20-30	4
M3	FC	27 (80)	70	0	JP-8	20-30	4
M60A3	ACC	23 (74)	71	1.5 NE	DF-2	10-15-20	6
M60A3	ACC	26 (78)	70	1.5 NE	JP-8	10-15-20	6
M60A3	FC	26 (78)	70	1.5 NE	DF-2	15-20	4
M60A3	FC	23 (74)	71	1.5 NE	JP-8	15-20	4

* ACC = full-throttle acceleration tests; FC = steady-speed fuel consumption tests.

The 2-mile long test tracks were measured with a vehicle odometer. Ample roadway was provided on both ends of the track to allow the vehicles to accelerate to the required test speed prior to reaching the starting marker.

2. Fort Benning, GA

The test track selected for the M3 and M60 vehicles at Fort Benning was a 2-mile smooth, straight, hard-packed sand and gravel road running east-to-west. The roadway had a slight gradient at both ends of the track.

3. Fort Hood, TX

The test track selected for the M88A1 vehicle at North Fort Hood was a 1-mile smooth, straight, hard-packed gravel road running east-to-west. The roadway had a slight gradient at the east end of the track. The preferred 2-mile distance could not be attained because of the hilly terrain prevalent at North Fort Hood.

F. Acceleration Test Procedure

The procedures used here were fully coordinated with TACOM representatives.(3)

Wide open throttle accelerations from standing start were performed on the vehicles at the following speeds:

M1009	20	30	40
M928	20	30	40
M113A2	10	20	30
M88A1	10	20	25
M1A1	10	20	25
M3	10	20	30
M60A3	10	15	20

Six individual runs were performed with each fuel: three in each direction. The time to reach speed was recorded for each specified speed. The time to reach speed was measured in a single run. The vehicle was operated a minimum of 2 miles at normal operating conditions

(approximately 25 percent throttle) after each three acceleration runs to stabilize engine temperature and performance.

G. Fuel Consumption Test Procedure

Two stakes were placed at each end of the measured course so that the stakes appeared aligned at the measurement points. With the transmission in high range, the vehicle was accelerated at normal driving conditions until desired speed was obtained prior to reaching the beginning marker. The appropriate speed was maintained until both markers were cleared. Fuel measurement started when the observer was in line with the beginning markers and stopped when the markers aligned at the opposite end of the track. The vehicle was turned around and the test repeated with the vehicle traveling in the opposite direction. A total of four runs were made at each speed, two runs in each direction. The only deviation from this procedure occurred with the M1A1 tank when it was felt that there may be insufficient fuel to complete testing. Only two runs were made with this vehicle, one run in each direction.

H. VEESS Evaluation

An observer with video-recording equipment was positioned on the upwind side of the test track, midway through the course, and a video-recording was made of smoke production on the M1A1, M88A1, and M3 operating at different modes.

TABLES 5, 6, and 7 outline the testing conditions for smoke readings using the VEESS system of these three vehicles. The vehicular smoke formation measurements during acceleration and steady-state tests were attempted, but it was impossible to distinguish the smoke from the dust.

I. Hot Starting

During the testing, observations were made of the engine startability and idle quality. The drivers were also questioned about drivability (hesitation, response to throttle changes, stumbling).

TABLE 5. M1 Static Smoke Formation Studies

Vehicle	Engine/Vehicle Condition	Fuel
M1	Idle (1200 rpm)	JP-8
M1	Attack Idle (1500 rpm)	JP-8
M1	No Load (3100 rpm)	JP-8
M1	Idle (1250 rpm)	DF-2
M1	Attack Idle (1500 rpm)	DF-2
M1	No Load (3100 rpm)	DF-2

TABLE 6. M88 Static Smoke Formation Studies

Vehicle	Engine/Vehicle Condition	Fuel
M88	1600 rpm	JP-8
M88	2350 rpm	JP-8
M88	1600 rpm	DF-2
M88	2350 rpm	DF-2

TABLE 7. M3 Static Smoke Formation Studies

Vehicle	Engine/Vehicle Condition	Fuel
M3	1400 rpm	JP-8
M3	2600 rpm	JP-8
M3	1400 rpm	DF-2
M3	2600 rpm	DF-2

VI. DISCUSSION OF RESULTS

In the following discussion, general observations such as hot starting, VEESS, and exhaust smoke are discussed. The acceleration and fuel consumption will then be summarized. These observations are followed by a vehicle-by-vehicle discussion of the acceleration and fuel consumption results. It is anticipated that those readers concerned with only the overall results can read the summary, then skip directly to the Conclusions and Recommendations sections of this report. For those interested in selected vehicles, more detailed discussions of the results are available.

A. Startability

The hot start, idle quality, and drivability observations are summarized in TABLE 8. Of particular interest is the startability of the AVDS-1790 engine (M88A1, M60A3). During the testing at both Forts Bliss and Hood, the engine was allowed to hot-soak for 5 minutes before attempting to restart. In both cases, the engine restarted on both DF-2 and JP-8, although longer cranking times were required with JP-8 at Fort Bliss (M88A1). At Fort Benning (M60A3), this procedure was altered to allow the engine to hot-soak for 15 minutes before restarting. After this soak, the engine would not restart on JP-8.

TABLE 8. Test Vehicle Observed Performance

Vehicle	Hot Starts*		Idle Mode		Drivability	
	DF-2	JP-8	DF-2	JP-8	DF-2	JP-8
M1009	Good	Good	Good	Good	Good	Good
M928	Good	Good	Good	Good	Good	Good
M113A2	Good	Good	Good	Good	Good	Good
M88A1 (Bliss)	Good	Additional Cranking Required	Good	Good	Good	Sluggish
M88A1 (Hood)	Good	Good	Good	Good	Good	Good
M1A1	Good	Good	Good	Good	Good	Good
M3	Good	Good	Good	Good	Good	Good
M60A3	Good	No Start**	Good	Good	Good	Good

* Hot starting procedure for all sites other than Fort Benning was to stop the engine while fully warm, wait 5 minutes, then attempt to start the engine following the recommended procedures.

** Although not confirmed, the hot starting problem appears to be due to special fuel system used during testing.

In order to restart the engine, the test fuel supply system was disconnected, and the M60A3 onboard system reconnected. The engine restarted within 2 seconds. This hot soak-failure to start-restart on the onboard system procedure was repeated twice.

One observation is that the engine restarted quickly on the onboard fuel system, even though 2 seconds was too little time for the JP-8 to be cleared from the fuel injection system. This quick start indicates that the startability problem may be one of inadequate fuel system pressurization by the external pump system with JP-8 present rather than the fuel itself. Unfortunately, the testing group had no facilities for pursuing this possibility further.

B. Exhaust Smoke

Exhaust smoke from particulate matter was measured only for the M1009 CUCV and M928 5-ton truck during the torque converter stall speed checks. The data are illustrated in Fig. 3.

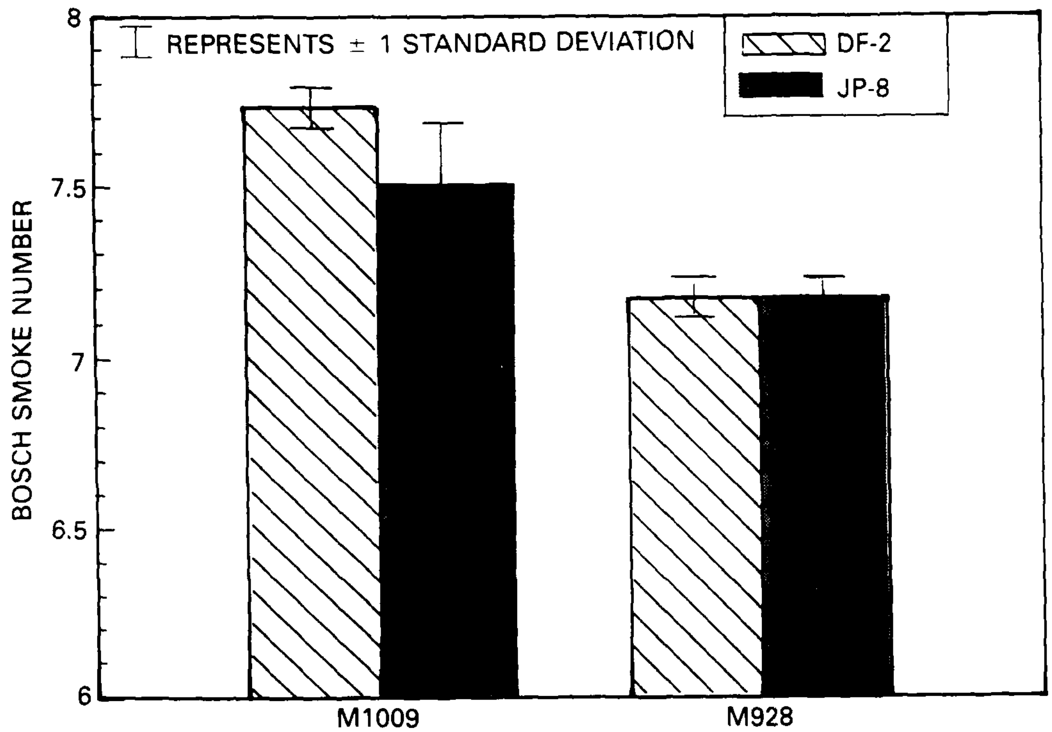


Figure 3. <u>Smoke production at torque converter stall speed</u>

With 90 percent confidence, there is no statistically significant difference in Bosch exhaust smoke number between the two fuels in either vehicle.

C. VEESS Smoke Production

Because of obscuration by dust, VEESS smoke production in moving vehicles could not be determined with either fuel in any of the vehicles (M1A1, M3, M60A3, and M88A1). Thus, only VEESS smoke production with the vehicles stationary could be determined. The DF-2 produced copious white smoke at all test conditions, although there were no visual indications of smoke with JP-8. Films documenting these tests were provided to Belvoir RDE Center.

D. Acceleration Comparisons

Full-throttle acceleration tests measure the time required to reach speed. For a given vehicle, the time indicates the maximum power available from the engine. The lower viscosity of JP-8 increases internal leakage in the high-pressure sections of the diesel engine injection pump and fuel injectors, thus lowering full rack (throttle) fuel delivery and decreasing maximum power.(4) Additional power losses are expected because of the lower volumetric heating value of JP-8 compared to DF-2, so the volume of fuel delivered with JP-8 would have lower energy content than the equivalent DF-2. Individual vehicle acceleration times obtained during the test are presented in the detailed vehicle discussions. These data are summarized in Fig. 4.

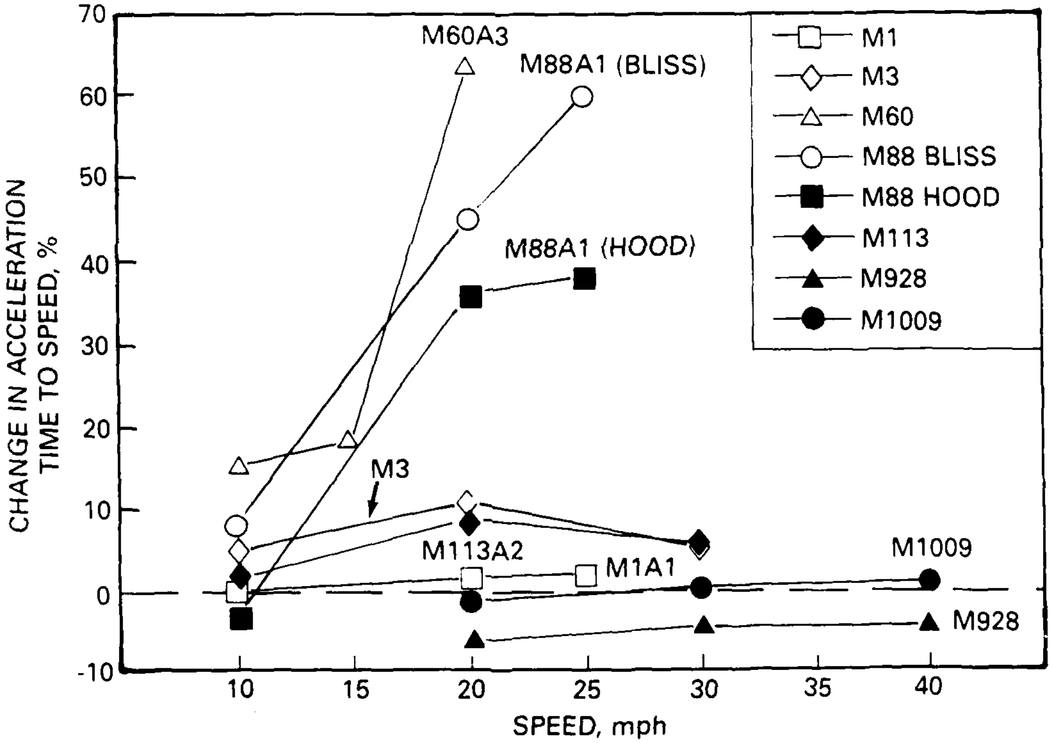


Figure 4. Change in acceleration times converting from DF-2 to JP-8

The vehicles that suffered the greatest increase in acceleration times and, therefore, the largest power loss, all use versions of the Teledyne Continental AVDS-1790 diesel engine. The injection system used on this engine apparently is sensitive to fuel viscosity. The change in

acceleration times was so large that the U.S. Army Tank-Automotive Command (TACOM) attempted to confirm these results through use of a vehicle performance computer model of the M88A1 and engine dynamometer data developed on JP-8. The modeling results shown in the Appendix closely match field data from the M88A1 vehicle at Fort Hood, thus substantiating these results.

The M928 5-ton truck was faster with JP-8 throughout the speed range tested. This vehicle is powered by a Cummins NHC-250 diesel engine that uses a Cummins PT injection system. This injection system is somewhat self-compensating for the leakage resulting from lowering fuel viscosity, and in the case of the M928, overcompensated somewhat, resulting in an increase in power with the lower viscosity fuel. The M3 IFV also uses a Cummins engine with a PT injection system, but in this case, the overcompensation was not observed.

The gas turbine engine powering the M1A1 main battle tank also has a fuel control system designed to compensate for changes in fuel viscosity and energy content, and as a result, there was no significant difference in performance between the two fuels.

The difference in acceleration rate between the two M88A1 recovery vehicles is believed to be primarily the result of injection system wear. The M88A1 at Fort Bliss was only available because it was "in too poor a shape to take into the field" and was being held in the motor pool in preparation for major maintenance. The retest at Fort Hood was specifically conducted in a newly reconditioned vehicle in "like new" condition. These two vehicle results thus probably bracket the range of acceleration losses to be expected.

E. Fuel Consumption Comparisons

If the engine combustion process is unaffected, substitution of JP-8 for DF-2 will increase fuel consumption slightly, simply because JP-8 contains a lower energy per volume of fuel than does DF-2. The actual difference in fuel consumption obtained in service could be different from that predicted from the relative heating values if there were changes in engine efficiency due to the property differences of the fuels. However, such engine efficiency differences would be small if they occur.

Measuring the vehicle fuel consumption differences in order to predict changes in required fuel volumes is complicated by second-order effects that are not easily estimated in short-term tests. If the use of JP-8 results in reductions in maximum power, then the slower accelerations and lower maximum speeds may also reduce the fuel consumption. This effect will not show up in the steady-state consumption tests conducted in this program, but any effect should be small.

Finally, the fuel consumption measured in this work should not be compared directly with fuel consumption in actual service. One source of potential error is the uncertainty in the course length. A larger potential difference is that these level road load measurements will produce lower consumption levels than would be experienced during accelerations or in uneven terrain. **The use for this preliminary data is primarily for comparative purposes.**

The JP-8 test fuel has 6.65 percent less energy content per gallon than the test DF-2 fuel. This percentage would be the expected increase in fuel consumption due to the fuel change. Fig. 5 presents the average increase in fuel consumption resulting from the change to JP-8

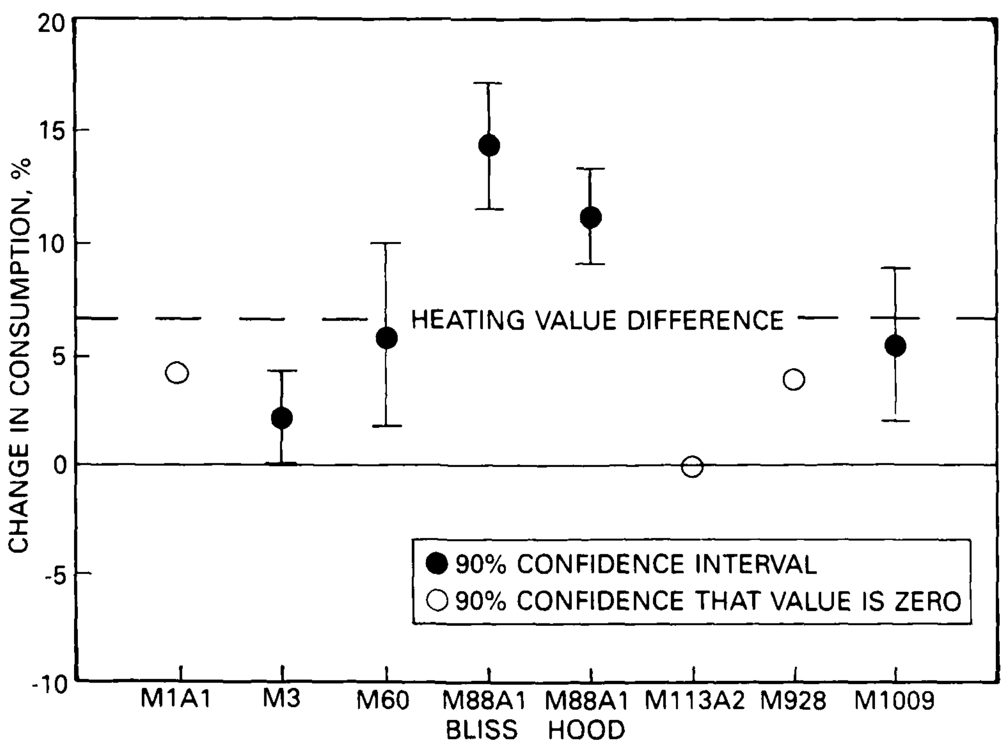


Figure 5. <u>Fuel consumption change converting from DF-2 to JP-8</u>

in each of the test vehicles. Except for the M88A1, under this limited testing methodology all vehicles had average consumption increases that were equal to or less than that predicted from the heating value alone. However, as indicated by the 90 percent confidence intervals shown by the vertical lines, the differences between these average values and the 6.65 percent predicted increase is not statistically significant. The open circles indicate that with 90 percent confidence, these differences are not statistically different than zero.

The large increase in fuel consumption in the M88A1 vehicle at Fort Bliss was distressing. The increase in acceleration times (power loss) would be an obvious result of a badly worn injection system. The fuel consumption increase indicates a reduction in engine thermal efficiency, which would not be expected. It is felt that the Fort Bliss M88A1 injection system had such high wear that adequate injection pressures could not be developed with JP-8. This wear resulted in a deterioration of the injection spray to such an extent that fuel mixing, and, therefore, combustion, was adversely affected. Since this vehicle was in an unacceptable state of maintenance, this data point should be considered either invalid or a worst case.

The reasons for the greater than expected fuel consumption increase with JP-8 in the Fort Hood M88A1 vehicles is not clear. The higher consumption with the Fort Bliss vehicle could be attributed to a worn injection system deteriorating combustion through poor spray formation. However, the reason that both of these vehicles would have unexpectedly high fuel consumption while the same engine design in the M60A3 does not cannot be explained at this time.

Except for the Fort Hood M88 exhaust temperature discussed later, none of the vehicles showed significant differences in exhaust temperatures or oil sump temperatures between the two fuels. The fuel temperatures tended to track the ambient temperature, as expected considering the external mounting. The fuel temperature was used to correct the fuel consumption.

F. Vehicle-by-Vehicle Discussion of Results

The following subsection discusses the test results on an engine-by-engine basis:

1. M1A1 Main Battle Tank

All testing with the M1A1 battle tank was conducted with the Nuclear Biological Chemical (NBC) system off. The fuel control system on the M1A1 is such that the fuel rate is varied at full power to maintain a maximum combustor liner temperature. Thus one would expect there would be no change in acceleration times when JP-8 was used, and this was the case, as seen in Fig. 6. The increase in fueling rate in order to maintain maximum power should result in a consumption increase equal in magnitude to the change in net volumetric heat of combustion between the two fuels. This rate of consumption assumes, of course, that the fuel change does not affect engine thermal efficiency.

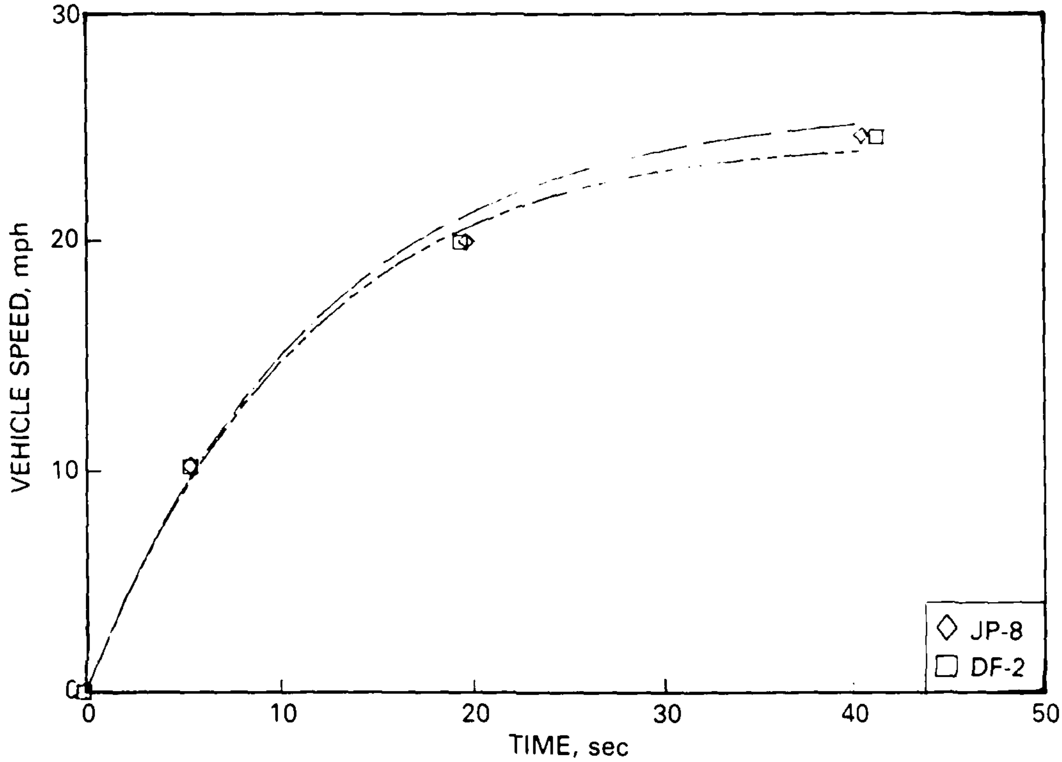


Figure 6. M1 acceleration DF-2 to JP-8 conversion

The partial load fuel consumption runs were only conducted twice with each fuel at each of the two test speeds. When converting from DF-2 to JP-8, the fuel consumption increased an average of 4.2 percent, with vehicle speed influencing the consumption increase (less

consumption increase at lower speed). This speed effect on the fuel consumption difference directionally agrees with the improvement in fuel atomization at low fuel flows that would be expected at low power levels. From a statistical sense, though, with 90 percent confidence, the increase in consumption could not be distinguished either from zero or the 6.65 percent estimated from the heating value. Preliminary data from Aberdeen Proving Ground also indicate a fuel consumption increase in the same range as indicated here.(5)

2. M3 Infantry Fighting Vehicle

The Cummins VTA-903T engine used in the M3, and similar M2, has the Cummins pressure-time (PT) injection system, which is partially self-compensating for fuel viscosity changes. The M3, when operated on JP-8, required an average 7.0 percent more time to reach speeds than with DF-2, as illustrated in Fig. 7. This change was not statistically significant at 90 percent confidence.

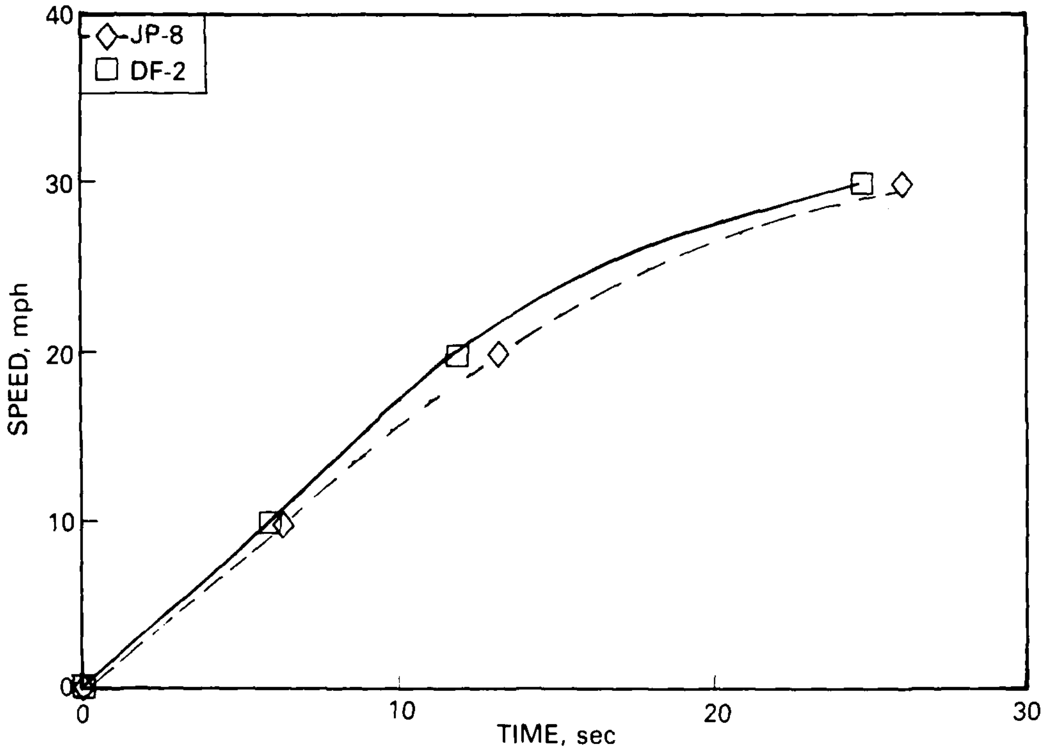


Figure 7. M3 acceleration

This difference in acceleration times is similar to preliminary data obtained from an M2A1 vehicle at Yuma Proving Ground (YPG). The YPG initial data showed an average of 8 percent increase in acceleration time when changing from DF-2 to JP-8. YPG also found no difference in maximum vehicle speed between the two fuels.(6)

Laboratory engine-dynamometer data in Fig. 8 from the U.S. Army Tank-Automotive Command with the Cummins VTA-903T engine that powers the M2 and M3 vehicles show less than 5 percent maximum power loss when converting to JP-8. This effect is shown in Fig. 8 for 85°F (29°C) and 195°F (90°C) fuel pump inlet temperatures and indicates that the impact of conversion to JP-8 should have only a small effect on vehicle acceleration for this vehicle family.

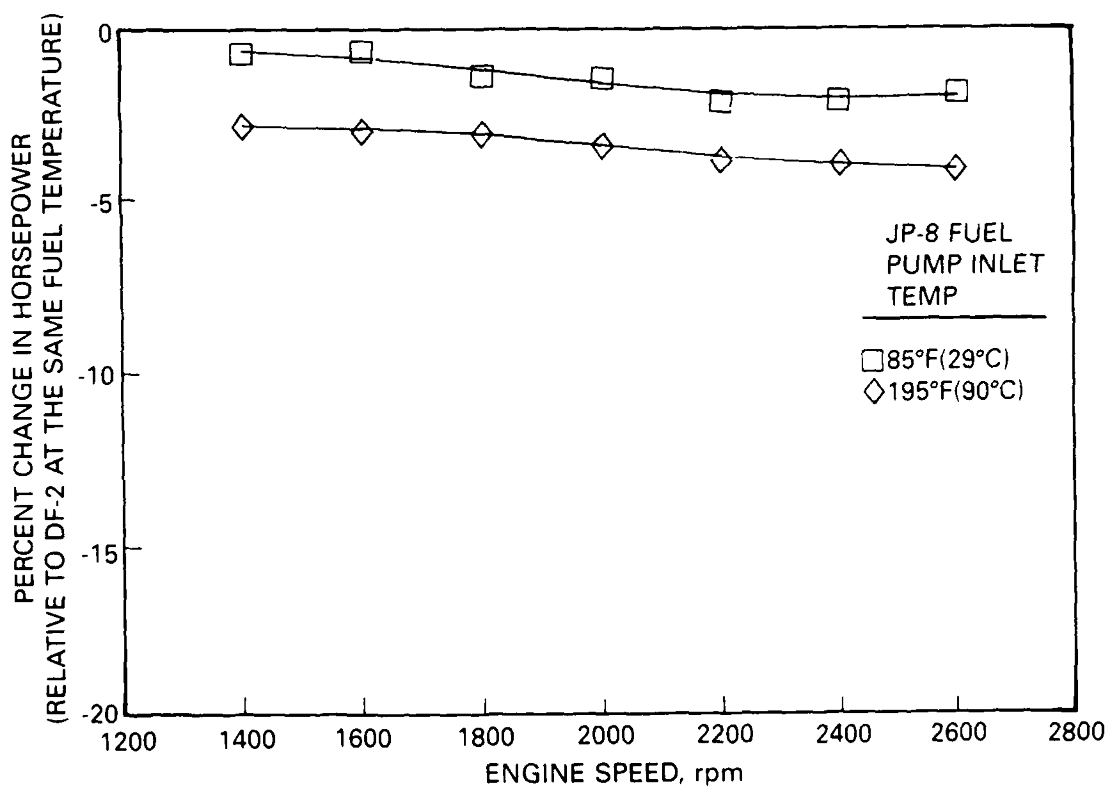


Figure 8. VTA-903T power loss with JP-8 fuel at 85° and 195°F fuel pump inlet temperature (from USA TACOM)

The change in vehicle fuel consumption between the two fuels averaged 2.2 percent higher consumption with JP-8. This percentage is less than the increase predicted by the heating value difference and may indicate a small improvement in thermal efficiency with the lower viscosity fuel. This increase in consumption was statistically significant at the 90 percent confidence level, and at the same confidence level was lower than the increase expected based on the heating values.

3. M60 Main Battle Tank

The AVDS-1790-2C engine in the M60A3 uses a rotary distributor-type injection pump with a single barrel and plunger assembly and separate injectors connected by high-pressure fuel delivery lines. This general type of injection system is more sensitive to fuel viscosity, with three high-pressure leakage paths (barrel and plunger, distributor, injectors). As a result, this engine would be expected to have greater power losses with JP-8, which would result in longer acceleration times with JP-8 compared to DF-2.

The acceleration results for the M60 are illustrated in Fig. 9. As anticipated, the acceleration time increases are larger than with many of the other vehicles tested. What is interesting is the large change in acceleration times for the 15 to 20 mph change. Although time to 10 and 15 mph increased by 15 and 18 percent, respectively, the time to 20 mph increased by 63 percent. It appears that 20 mph is near the top speed of this vehicle when using JP-8.

The increase in fuel consumption due to the change to JP-8 averaged 7.0 percent, which is in agreement with that predicted by the volumetric heating value change.

4. M88 Recovery Vehicle

The AVDS-1790-2DR engine used in the M60 main battle tank and M88A1 recovery vehicle is expected to suffer the largest power loss of any of the engines tested. Dynamometer data from the engine manufacturer and TACOM shows that power losses of the order of 7 percent are expected. In the initial tests conducted at Fort Bliss, however, the observed acceleration time losses were much greater, ranging from 8 to almost 60 percent longer acceleration times.

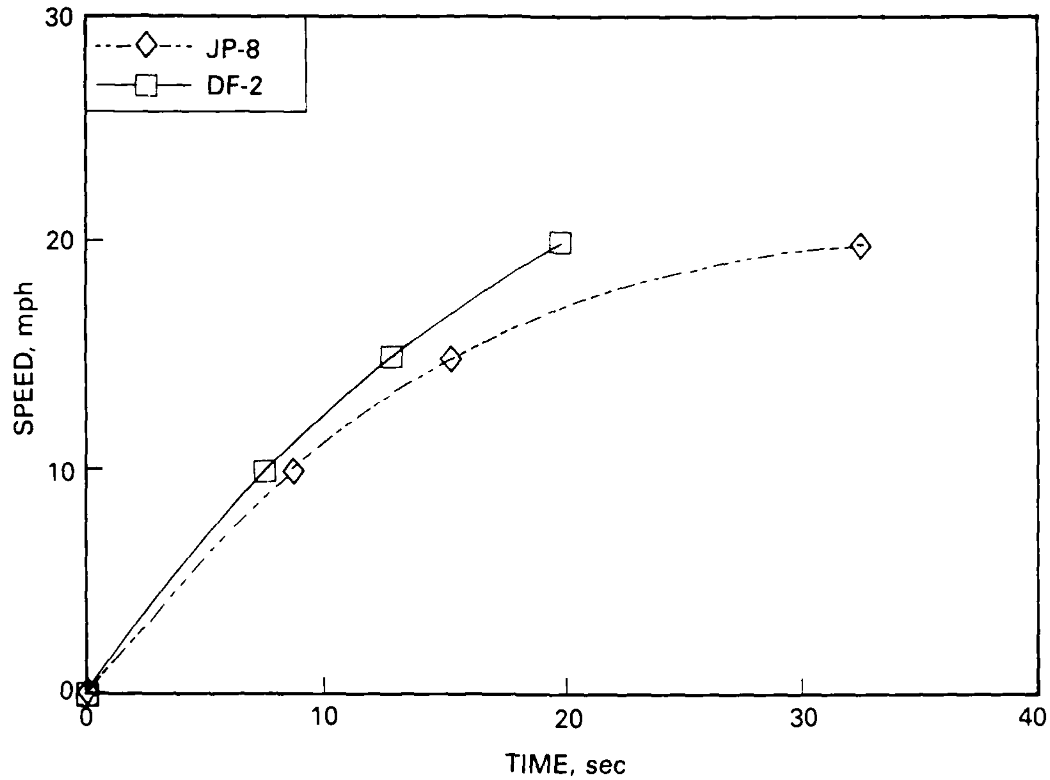


Figure 9. M60 acceleration

It was believed that these large changes in acceleration times are the result of large leakages caused by high wear in the injection pump and injectors. According to the vehicle operator, the test vehicle was available only because it was in too poor a condition to be used in the current field exercises. It was also described as being low on power already. If the engine injection equipment was suffering from high wear in the injection system, then the introduction of a low viscosity fuel would only increase the leakage already present. In fact, based on the fuel consumption data, it was felt that the injection system internal leakage with JP-8 was so high that injection pressures were degraded enough to adversely affect fuel atomization and combustion.

The initial reaction was to treat these data as being fatally flawed. However, the test vehicle was still in use, although only within the motor pool. These data may be an indication of a worst case for JP-8 conversion, and set an upper limit on possible adverse power impacts.

Arrangements were made to test a second, almost new M88A1 at Fort Hood, TX. As expected, this vehicle performed much better than the Fort Bliss vehicle on diesel fuel. Fig. 10 compares the acceleration rates of the two vehicles on diesel fuel. On average, with DF-2, the M88A1 at Fort Hood was 15 percent faster than the first vehicle tested. When this second M88A1 vehicle was converted to JP-8, the vehicle acceleration times increased 27 percent at the higher speeds. These apparent power losses are large but, nonetheless, much smaller than the first M88 tested. The acceleration time increases for the two vehicles are compared in Fig. 11.

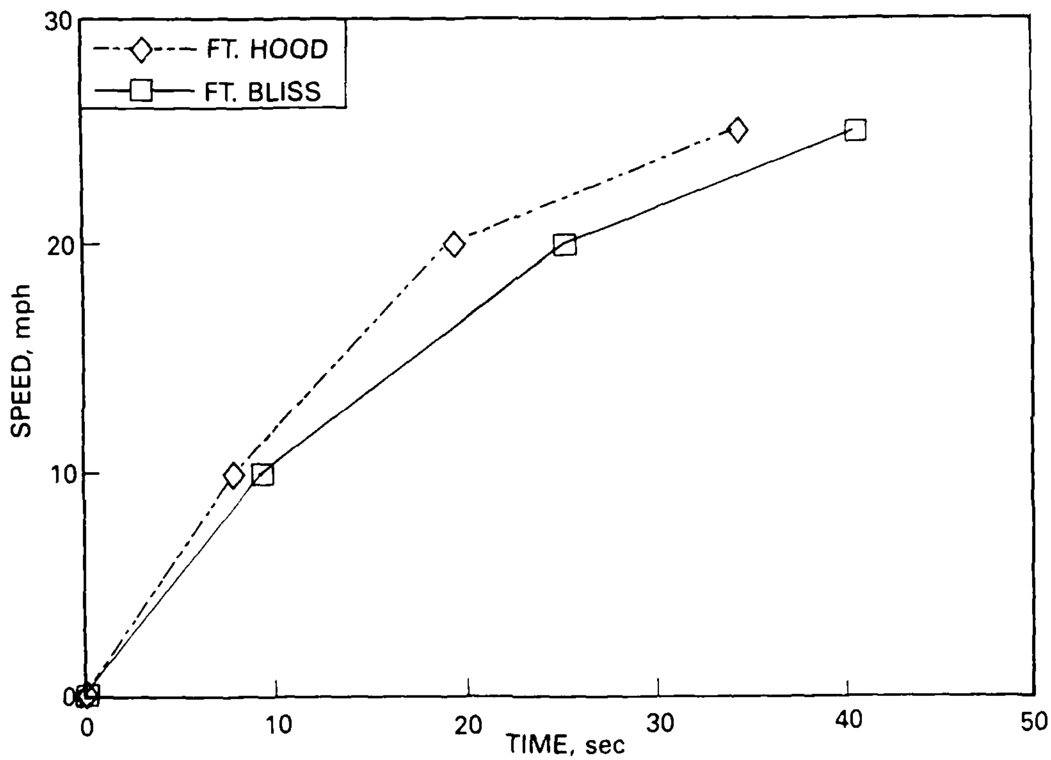
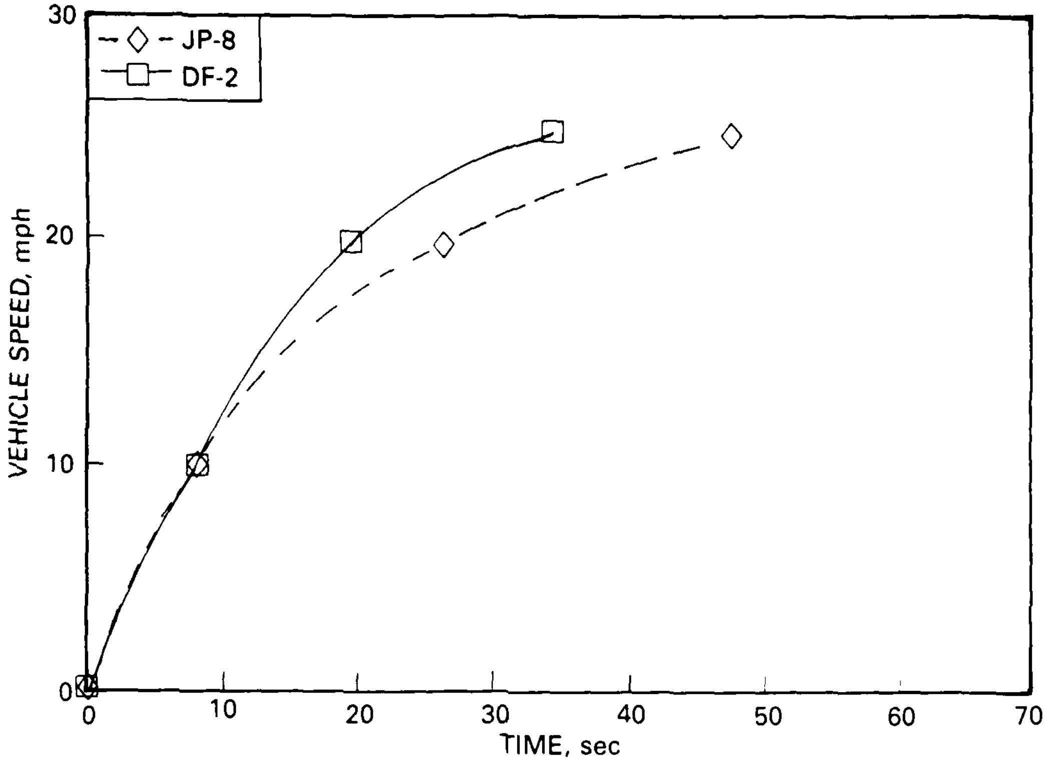
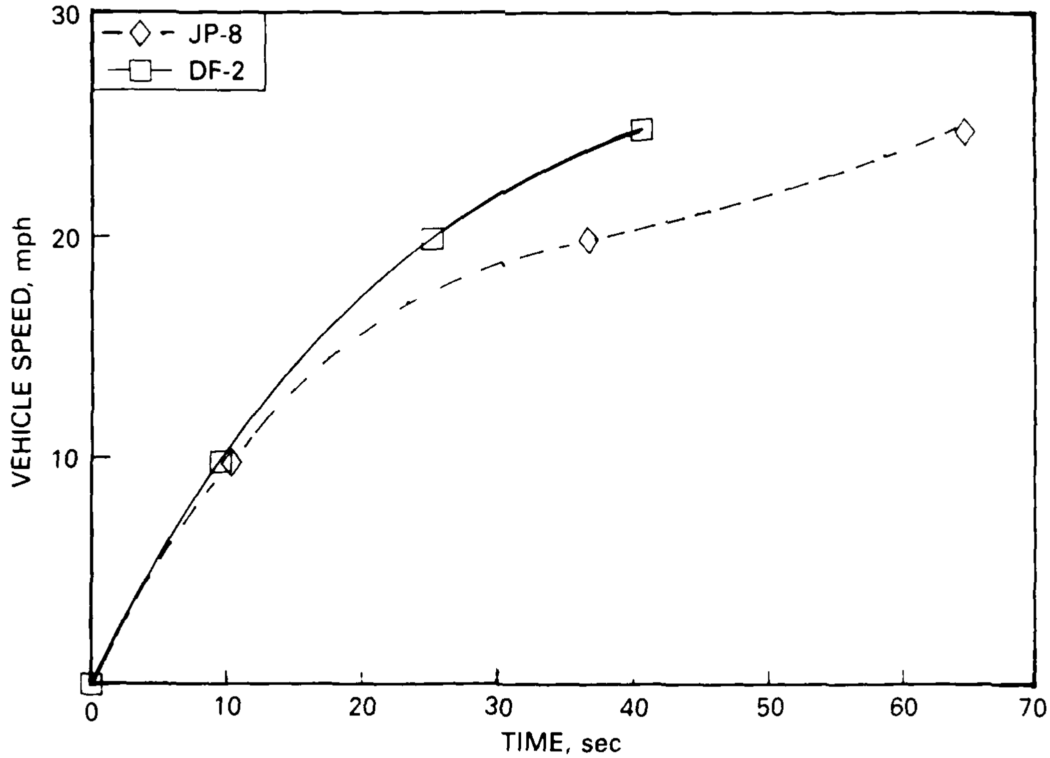


Figure 10. M88A1 vehicle comparison with DF-2

The Fort Bliss M88A1 had an average increase in fuel consumption of 15 percent, far above that expected. This large increase is an indication that the combustion process must have been degraded. The M88A1 vehicle at Fort Hood, TX had an 11 percent increase in consumption. Although still higher than expected, this percentage is more in line with the heating value difference and the fuel consumption difference seen in the M60 vehicle.



Fort Hood



Fort Bliss

Figure 11. **M88A1 at Forts Hood and Bliss**

One oddity that was noted concerned the M88A1 exhaust temperature during the acceleration tests at Fort Hood. The exhaust temperature with DF-2 was virtually constant during the runs. With JP-8, however, the exhaust temperature increased throughout the run; by the end of each run, the temperature was over 100°F higher than the temperatures with DF-2 as shown in Fig. 12. This behavior was not seen in the M60 testing, where exhaust temperatures with the two fuels were similar. Unfortunately, due to thermocouple problems, exhaust temperature data were not available from the Fort Bliss M88A1.

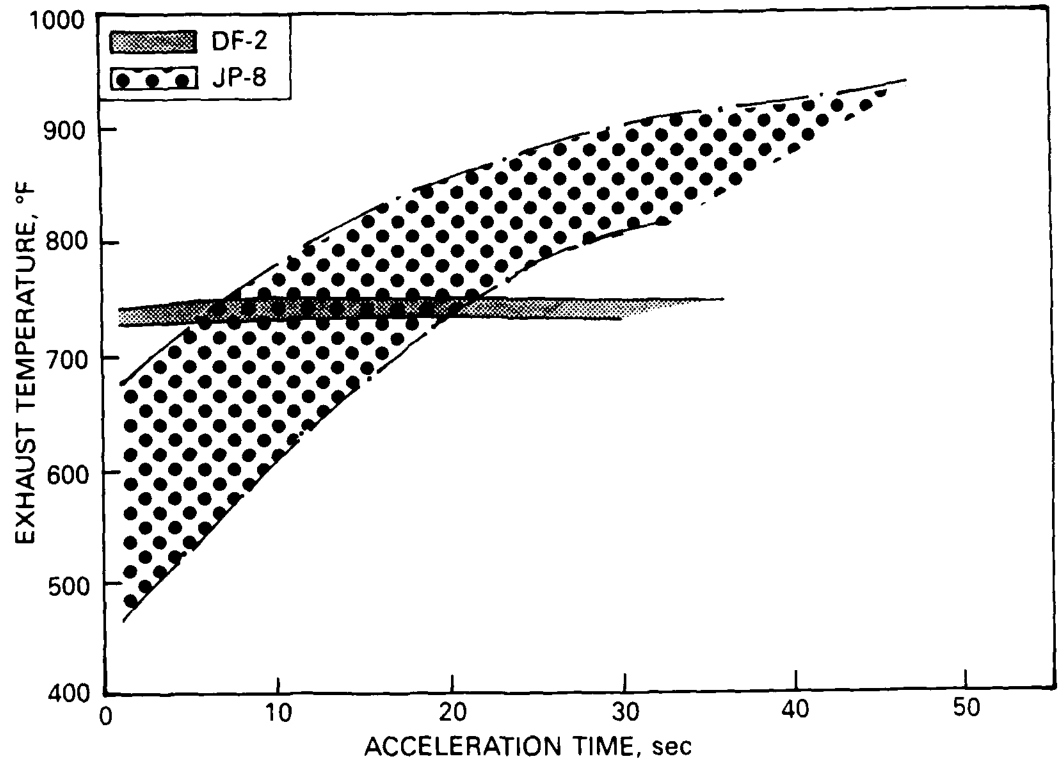


Figure 12. <u>**Hood M88 exhaust temperatures DF-2 and JP-8**</u>

The performance change in the M88A1 recovery vehicle was so large that there was concern about the validity of the data. TACOM was contacted and agreed to attempt to validate the acceleration data through the use of a vehicle performance model, using engine data on JP-8 previously obtained at TACOM's laboratory. The results are given in the Appendix. The vehicle performance predicted by its model closely matches the actual field results.

5. M113A2 Armored Personnel Carrier

Considerable laboratory data have been generated with JP-8 in the Detroit Diesel two-cycle diesel engine family. The Detroit Diesel 6V-53N engine, which powers the M113A2, uses a high-pressure unit injector. In the laboratory (Fig. 13), this engine family loses 3 to 8 percent in maximum power when changing to JP-8. This power loss agrees well with the change in acceleration times observed in the vehicle. The differences observed in acceleration times to both 20 and 30 mph were statistically significant.

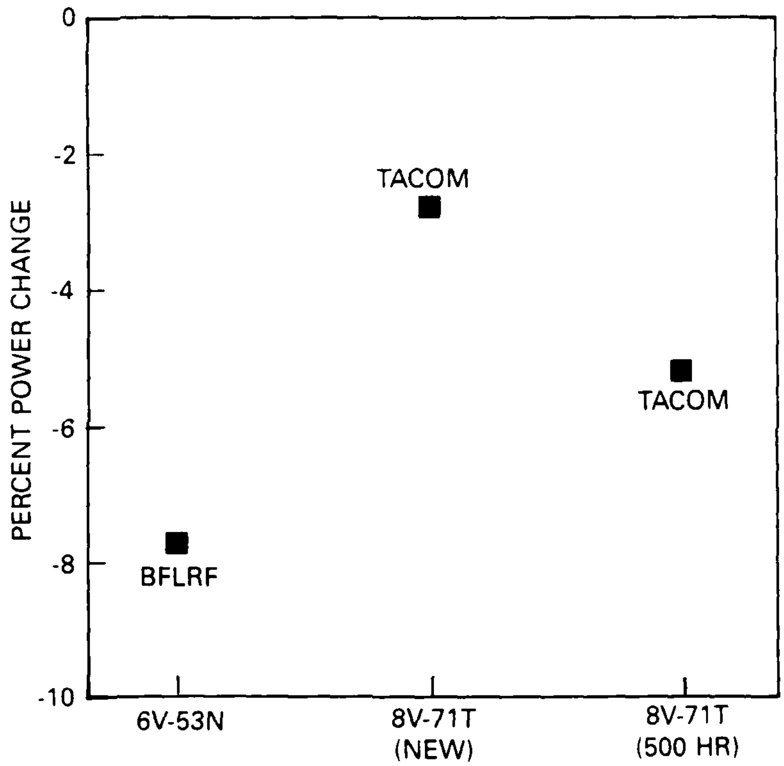


Figure 13. DDC 6V-53 power loss comparison DF-2 to JP-8

The fuel consumption was virtually identical between the two fuels. This fact was surprising since laboratory tests had indicated that these DDC engines generally have small increases in thermal efficiency with the lighter JP-8, but not enough to overcome the differences in heating value.(7) The thermal efficiency improvements noted in laboratory testing of a similar engine did show that these improvements were greatest at low engine speeds. This speed effect on efficiency may help account for the unexpected lack of fuel consumption increase in the vehicle testing.

6. M928 5-Ton Truck

The Cummins NHC-250 engine used in the M928 5-ton truck has a fuel injection system similar to that in the M2/M3. To some extent, this injection system self-compensates for the leakage that results from low-viscosity fuels. In testing with JP-8, the injection system overcompensates slightly, resulting in slight power increases when changing from DF-2 to JP-8. This same behavior is seen in the changes in acceleration times when the M928 was changed from DF-2 to JP-8 (Fig. 14). The vehicle was slightly faster with JP-8 than DF-2, although these differences were not statistically significant.

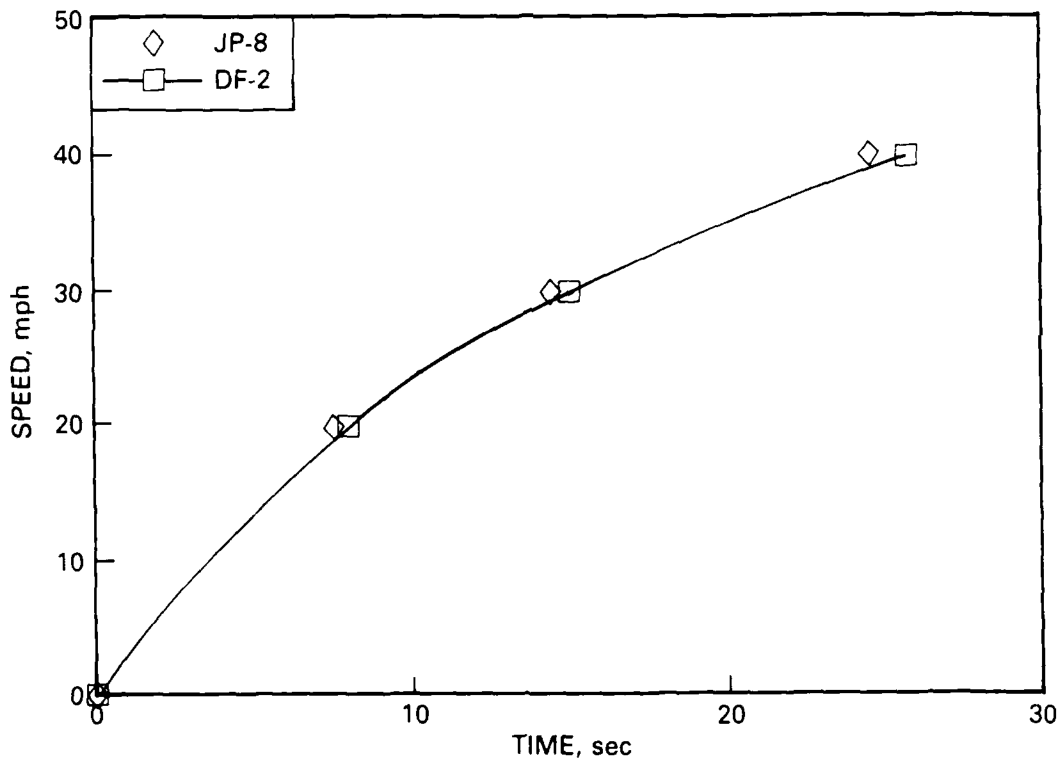


Figure 14. M928 acceleration

Fuel consumption in the M928 vehicle increased by 4 percent when changing from DF-2 to JP-8. This smaller than expected fuel consumption increase is in line with laboratory results at BFLRF, which showed a small improvement in thermal efficiency with JP-8.

7. M1009 Vehicle

The M1009 acceleration times were virtually unchanged by the substitution of JP-8, although there was some speed effect (Fig. 15). JP-8 produced slightly faster acceleration to 20 mph, but was slower at 40 mph. These data match directionally the dynamometer data obtained at BFLRF on the GM 6.2L engine used in this vehicle. The dynamometer data are summarized in Fig. 16. Dynamometer data showed that the engine power loss with JP-8 is engine speed sensitive, with larger power losses occurring at high engine speeds. This speed effect is also evident in the acceleration time data. However, the vehicle acceleration data do not show the large power loss expected from the dynamometer data, which show power losses with JP-8 of approximately 7 percent. The differences in acceleration times between the two fuels are not significantly different at the 90 percent confidence level.

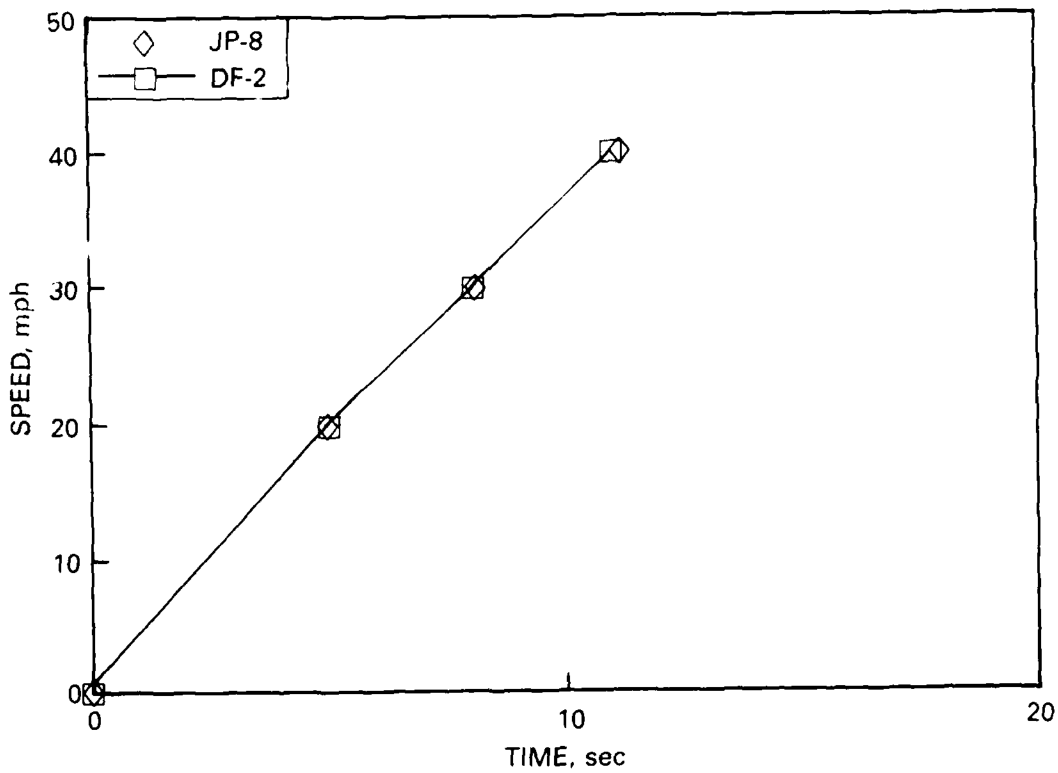


Figure 15. M1009 Acceleration

The fuel consumption of the M1009 vehicle increased by 5.2 percent when changing from DF-2 to JP-8. This increase was not statistically different from the 6.6 percent predicted value, but at the 90 percent confidence level, it was different than zero.

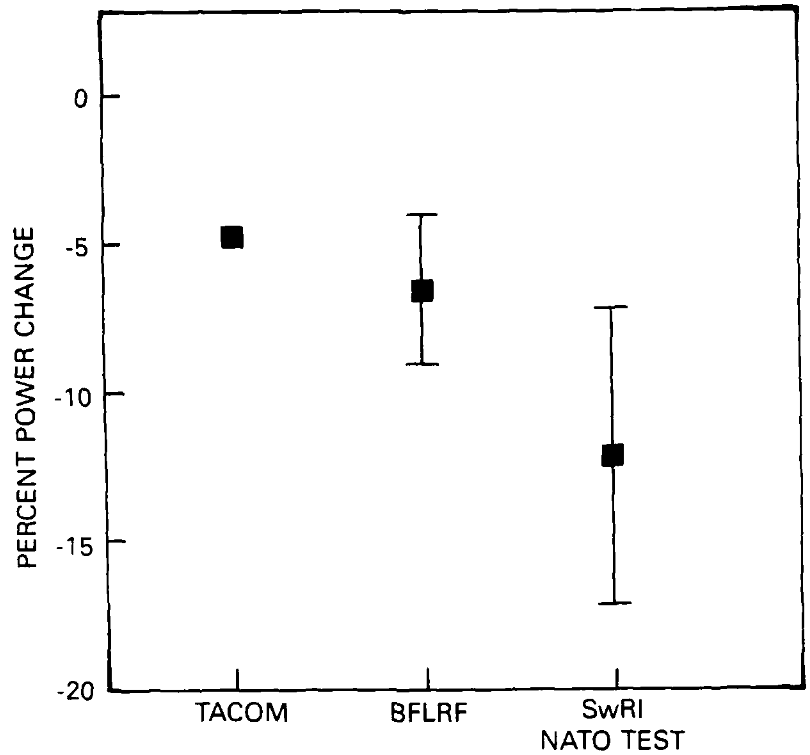


Figure 16. GM 6.2L power loss comparison DF-2 to JP-8

VII. CONCLUSIONS

- Substitution of JP-8 for DF-2 reduced the acceleration rates, and thus power, of all the vehicles tested except for the M928 and M1009.

- Use of JP-8 increased the maximum acceleration rate in the M928 and did not change the acceleration capability of the M1009.

- Of all vehicles tested, only those vehicles powered by the AVDS-1790 series engine (M60A3 and M88A1) had increases in acceleration times of more than 10 percent.

- All the vehicles tested, other than the two M88A1 light recovery vehicles, had fuel consumption increases with JP-8 that were at or below that predicted by the heating value difference between the two fuels.

- The fuel consumption increased with JP-8 in the M88A1 was higher than predicted. The reason for this greater than expected consumption is not apparent at this time.

- No drivability or idle problems occurred with any of the test vehicles.

- Of the vehicles, only the M60A3 had hot starting problems with JP-8. The hot starting problem that occurred with the M60A3 appears to be a result of the special fuel supply system for testing purposes rather than an inherent problem with JP-8. However, sufficient testing to verify this possible cause has not been done.

VIII. RECOMMENDATIONS

- Further testing on hot starting with JP-8 in the M60A3 vehicle needs to be conducted to verify the cause of the observed problem.

- Further testing with the M88A1 and M60A3 vehicles is required to determine if the performance losses observed here will jeopardize their mission operation and, if necessary, what options may be available.

- Further investigation should be made into the larger than anticipated fuel consumption increase with JP-8 in the M88A1, which did not occur in the M60A3.

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APPENDIX

TACOM M88A1 Field Performance Comparison
DF-2 vs. JP-8

By

Fred Zimmerman, AMSTA-RGT

Memo for File

Subject: M88A1 field performance comparison DF-2 vs. JP-8.

Discussion: It has been reported that a recent trial comparing automotive performance using DF-2 & JP-8 on the M88A1 has demonstrated extremely poor acceleration on JP-8. These results are much below our current predictions based on the JP-8 work done in the propulsion lab on the AVDS-1790 engine. I discussed this project with Mr. Ed Owens, (Southwest Research Institute) who was running the investigation for Mr. Mario Laperia's group at Ft. Belvoir. The testing was preformed on two different vehicles in an effort to gain confidence in the data. The vehicles were modified to add a special fuel tank for test purpose so that fuel consumption could be monitored and clean contamination free fuel changes could be made. The vehicles were loaded with a three man crew and approximately 150 lbs. of additional gear including the extra fuel tank. The test was conducted on a straight level road and the time to 10, 20 & 25 MPH was recorded for 6 runs with each fuel. The results were as follows:

Fort Bliss Vehicle condition "in too poor of shape to take into the field".

Ambient Temp. 93 F. Fuel Temp. 100 - 105 F. Fuel Press. 14psi

Speed MPH	Average Time (6 runs)* DF-2	JP-8	% Diff.
0 - 10	9.4	10.2	8.5
0 - 20	25.2	36.6	45.2
0 - 25	40.6	64.7	59.3

Tested starting in third range with no shift.

Fort Hood Vehicle condition "like new".

Ambient Temp. 90 F. Fuel Temp. 110 F. Fuel Press. 14psi

Fuel consumption:

15MPH -	DF-2	139.8 Gal/100 Mi.	
	JP-8	157.0 Gal/100 Mi.	12.3% higher
20MPH -	DF-2	120.0 Gal/100 Mi.	
	JP-8	133.0 Gal/100 Mi.	10.8% higher

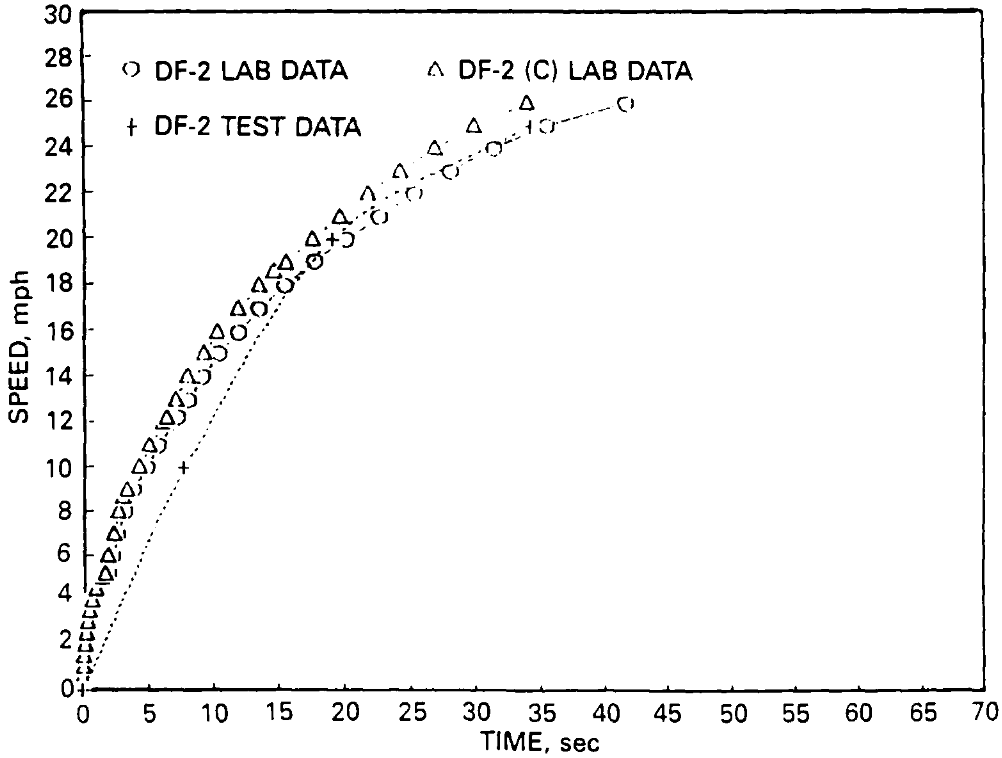
Speed MPH	Average Time (6 runs)* DF-2	JP-8	% Diff.
0 - 10	7.9	7.7	-2.5
0 - 20	19.3	26.3	36.3
0 - 25	34.4	47.4	37.8

One additional test was made on the M60 to check the same engine with a different transmission. The results are as follows:

M60 Data

Speed MPH	% Diff.	Fuel Consumption
0 - 10	15.0%	7.0% higher
0 - 15	18.0%	
0 - 20	63.0%	

Conclusion: During the JP-8 performance test on the AVDS-1790 engine at TACOM Lab there were four sets of torque data generated. Two of these curves need corrected due to a load cell calibration error found during the test. This corrected data and the other set of test curves were used as input into the Allison Transmission Division (ATD) SCAAN model. As can be seen in the attached curves the field test data falls within the predicted range of the model. Based on this limited data sample it is concluded the test performance is representative of the expected performance loss when using JP-8 fuel. The flatness of the JP-8 velocity curve indicates that the vehicle is power limited. Additional engine power loss (for any reason) will result in a disproportionate loss in acceleration performance.


DF-2 LAB DATA
DF-2 (C) LAB DATA
DF-2 TEST DATA
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TIME, sec
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18
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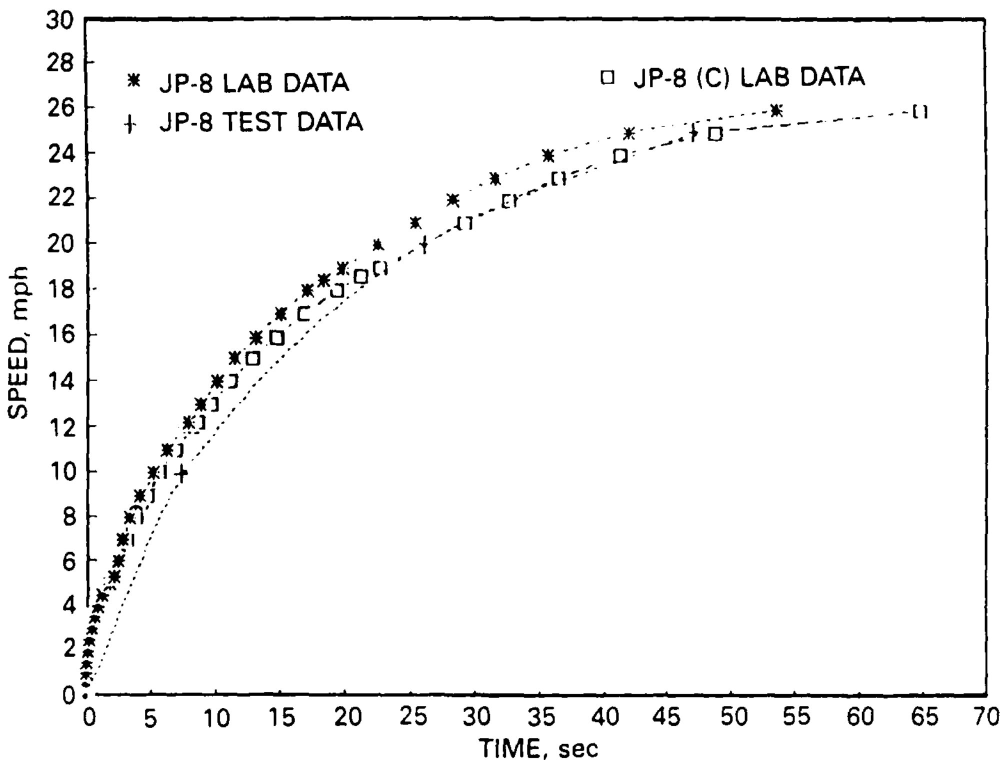
65
70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JP-8 (C) LAB DATA
JP-8 TEST DATA
SPEED, mph
TIME, sec
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2
4
6
8
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